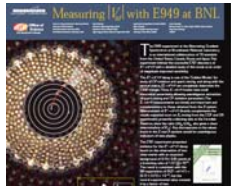
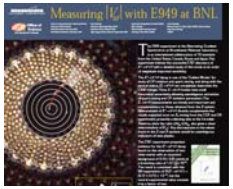


New Results from BNL E949
$K^+ \to \pi^+ \gamma\gamma$ and $\pi^0 \to \nu\ \bar{\nu}$

Peter S. Cooper
Fermi National Accelerator Laboratory
(*for the BNL E949 collaboration*)

E949 is a high rate K^+ decay at rest experiment with the primary goal of determining |Vtd| via a measurement of the branching ratio of the ultra-rare charged kaon decay $K^+ \to \pi^+ \nu\ \bar{\nu}$. I report here related limits from the decays $K^+ \to \pi^+ \gamma\gamma$, $K^+ \to \pi^+ \gamma$ and $\pi^0 \to \nu\ \bar{\nu}$.

E949 Collaboration



ELSEVIER

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Physics Letters B 623 (2005) 192–199

PHYSICS LETTERS B

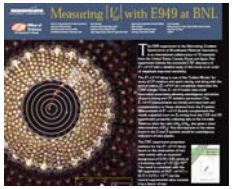
www.elsevier.com/locate/physletb

Search for the decay $K^+ \to \pi^+\gamma\gamma$ in the π^+ momentum region $P > 213$ MeV/c

E949 Collaboration

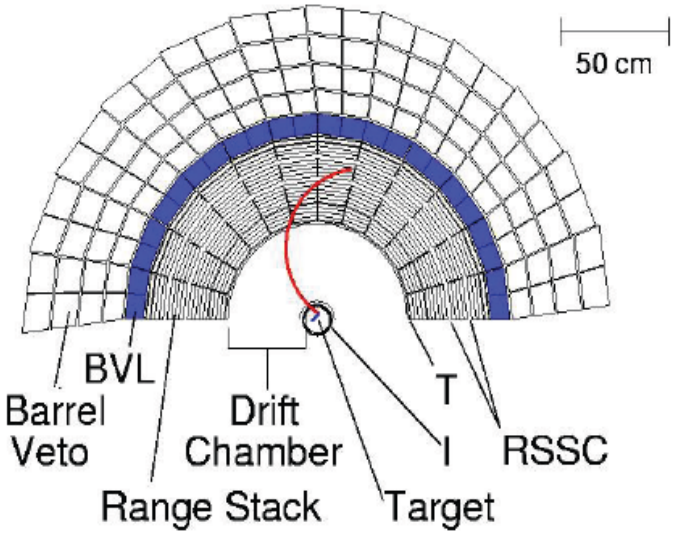
A.V. Artamonov [a], B. Bassalleck [b], B. Bhuyan [c,1], E.W. Blackmore [d], D.A. Bryman [e], S. Chen [d,2], I.-H. Chiang [c], I.-A. Christidi [f], P.S. Cooper [g], M.V. Diwan [c], J.S. Frank [c], T. Fujiwara [h], J. Hu [d], D.E. Jaffe [c], S. Kabe [i], S.H. Kettell [c], M.M. Khabibullin [j], A.N. Khotjantsev [j], P. Kitching [k,3], M. Kobayashi [i], T.K. Komatsubara [i,*], A. Konaka [d], A.P. Kozhevnikov [a], Yu.G. Kudenko [j], A. Kushnirenko [g,4], L.G. Landsberg [a], B. Lewis [b], K.K. Li [c], L.S. Littenberg [c], J.A. Macdonald [d,*], J. Mildenberger [d], O.V. Mineev [j], M. Miyajima [l], K. Mizouchi [h], V.A. Mukhin [a], N. Muramatsu [m], T. Nakano [m], M. Nomachi [n], T. Nomura [h], T. Numao [d], V.F. Obraztsov [a], K. Omata [i], D.I. Patalakha [a], S.V. Petrenko [a], R. Poutissou [d], E.J. Ramberg [g], G. Redlinger [c], T. Sato [i], T. Sekiguchi [i], T. Shinkawa [o], R.C. Strand [c], S. Sugimoto [i], Y. Tamagawa [l], R. Tschirhart [g], T. Tsunemi [i,5], D.V. Vavilov [a], B. Viren [c], N.V. Yershov [j], Y. Yoshimura [i], T. Yoshioka [i,6]

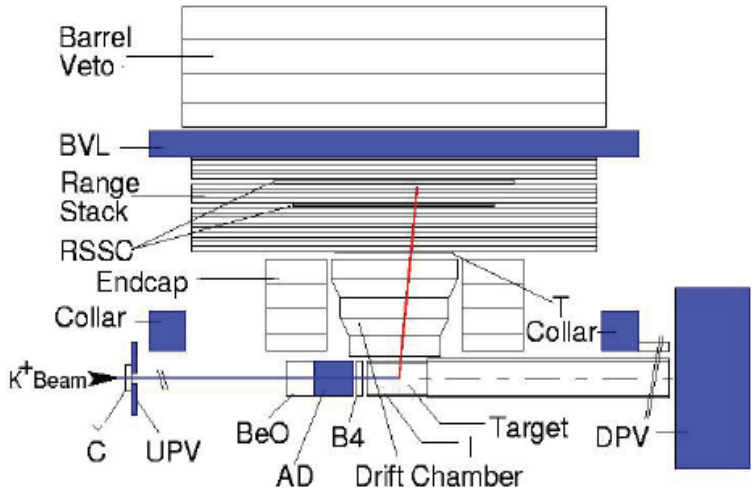
[a] *Institute for High Energy Physics, Protvino 142 280, Moscow Region, Russia*
[b] *Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM 87131, USA*
[c] *Brookhaven National Laboratory, Upton, NY 11973, USA*
[d] *TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3*
[e] *Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[f] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA*
[g] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[h] *Department of Physics, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan*
[i] *High Energy Accelerator Research Organization (KEK), Oho, Tsukuba, Ibaraki 305-0801, Japan*
[j] *Institute for Nuclear Research RAS, 60 October Revolution Pr. 7a, 117312 Moscow, Russia*
[k] *Centre for Subatomic Research, University of Alberta, Edmonton, Canada T6G 2N5*
[l] *Department of Applied Physics, Fukui University, 3-9-1 Bunkyo, Fukui 910-8507, Japan*
[m] *Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan*
[n] *Laboratory of Nuclear Studies, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan*
[o] *Department of Applied Physics, National Defense Academy, Yokosuka, Kanagawa 239-8686, Japan*



E949 Detector in LESB II at BNL

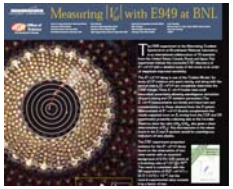
E787/E949 was designed primarily to observe the rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$, but other rare modes are accessible, particularly those involving photons

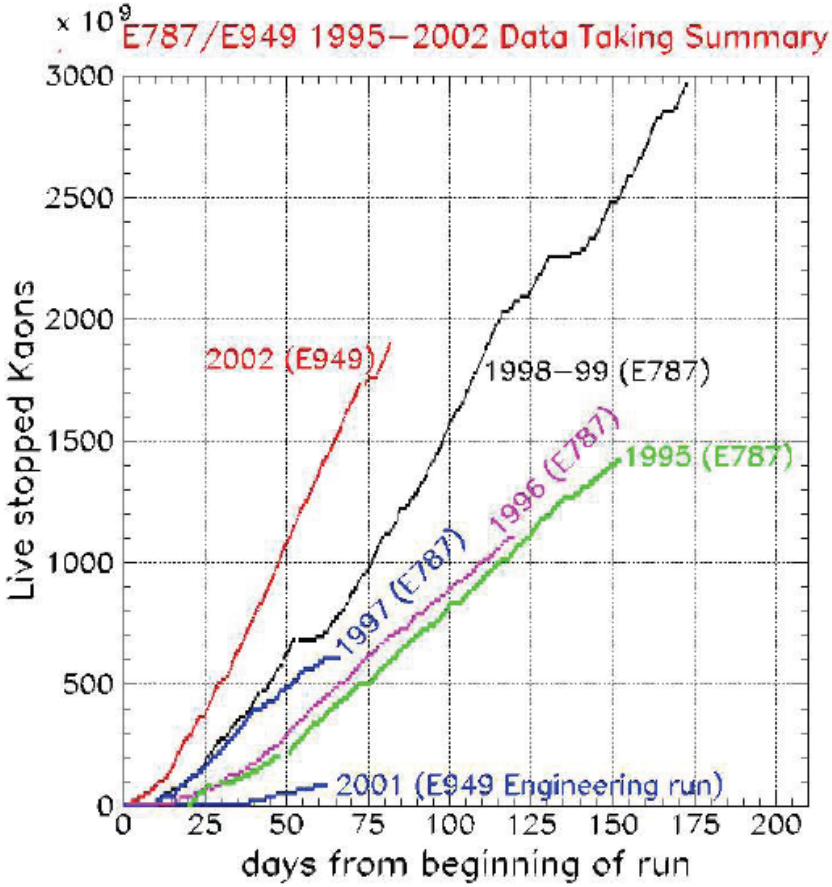




- Incoming beam (~700 MeV/c) tagged by Cerenkov, dE/dx counters
- Stopped kaon beam. Wait ~2ns for K decay (reject beam π). High geometrical acceptance.
- K decay-products momentum analyzed in 10 kG B field.
- Stopped decay pion. Measurement of particle range and energy. Observation of $\pi \to \mu \to e$ decay sequence for μ rejection.
- Photon detectors surround everything (E949 PV upgrades shown in blue).

E787 / E949 Data Taking Summary





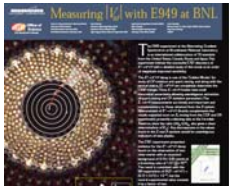
This plot is for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ triggers but gives a rough idea of the kaon exposure.

Recall, E949 ran for 12 weeks in 2002 (out of 60 weeks approved) and has not run since then.

2002 run:

- AGS main power supply problem.
  20% worse duty cycle cf. E787
  Lower p momentum ⇒ ~10% loss in K flux
- K/π separator problems

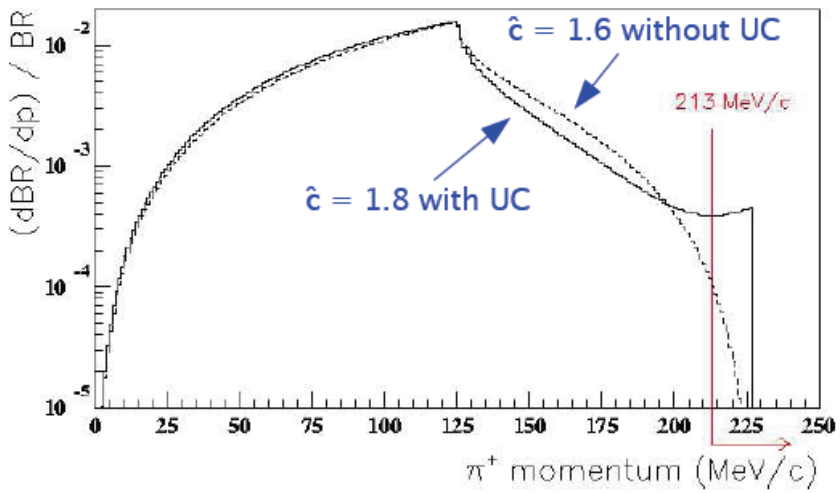
$K^+ \to \pi^+\gamma\gamma$ Introduction



At $O(p^4)$ in ChPT, $BR(K^+ \to \pi^+ \gamma \gamma)$ and spectrum shape depend on a single parameter, $\hat{c}$

So-called "unitarity corrections" (UC) dominate at the next order ($O(p^6)$)
- E787 analysis had a slight preference for UC, but not conclusive

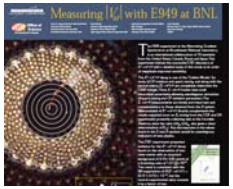
Effect of UC is most dramatic at the π^+ kinematic endpoint (low $M(\gamma\gamma)$)
- E949 focused on this region



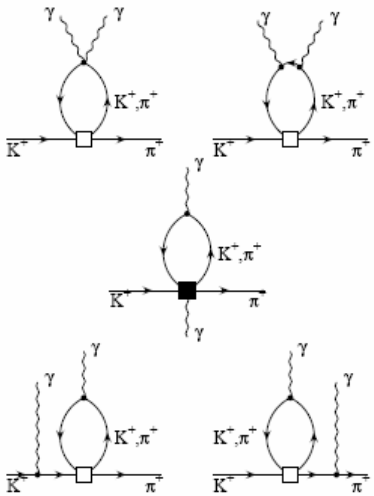
New in E949
- Better trigger, no online prescale!
- Thicker, brighter barrel photon detector

	K exposure	# of triggers
E787	3.1×10^{10}	7.3×10^5
E949	1.19×10^{12}	1.1×10^7

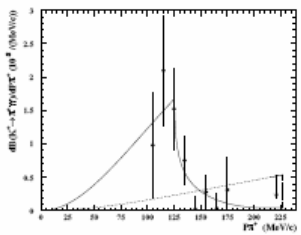
$K^+ \to \pi^+\gamma\gamma$ in Chiral Perturbation Theory



leading contribution at $O(p^4)$

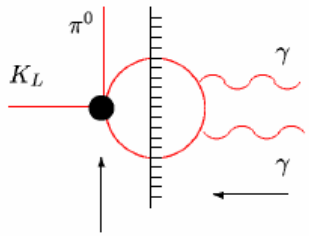


undetermined coupling-constant $\hat{c}$



NLO contribution at $O(p^6)$

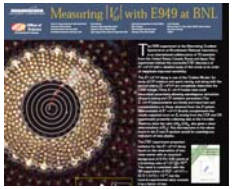
- "unitarity" corrections with $\hat{c}$

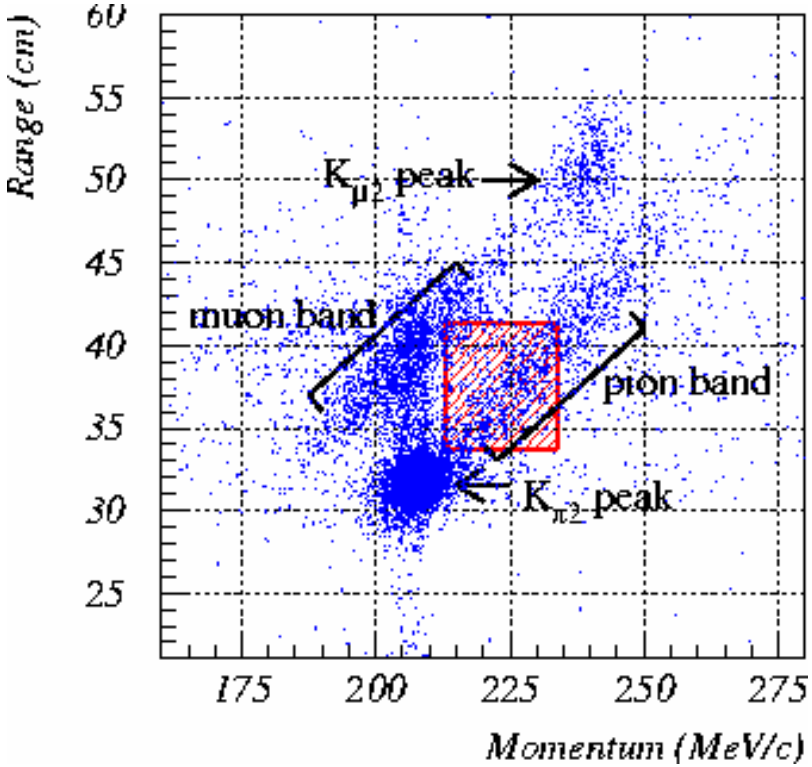


$$A(K \to 3\pi) = a + b\,Y + c\,Y^2 + d\,X^2$$

- Vector-Meson exchange
  negligible in $K^+ \to \pi^+\gamma\gamma$
  important in $K_L^0 \to \pi^0\gamma\gamma$ (a_v)
- other new dynamics ??

$K^+ \rightarrow \pi^+\gamma\gamma$ Offline Analysis





Backgrounds:

$K^+ \rightarrow \pi^+\pi^0$ ($K\pi 2$)

- π^+ kinematics measured
- Photon energies/angles mis-measured
- Or photon overlaps charged track

$K\pi 2$ with K Decay In Flight (DIF)

- π^+ Kinematics measured
- Fakes K decay at rest

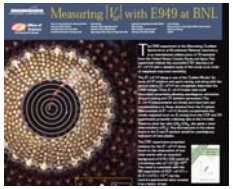
$K^+ \rightarrow \mu^+\nu\gamma$, $\pi^0\mu^+\nu\gamma$ or $K\pi 2$ with π DIF

- μ^+ kinematics measured
- $\pi \rightarrow \mu \rightarrow e$ decay sequence fooled

Two beam particles

- Suppressed with good segmentation and timing in the K tracking system

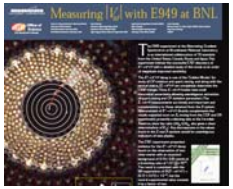
Backgrounds, Acceptance, Sensitivity

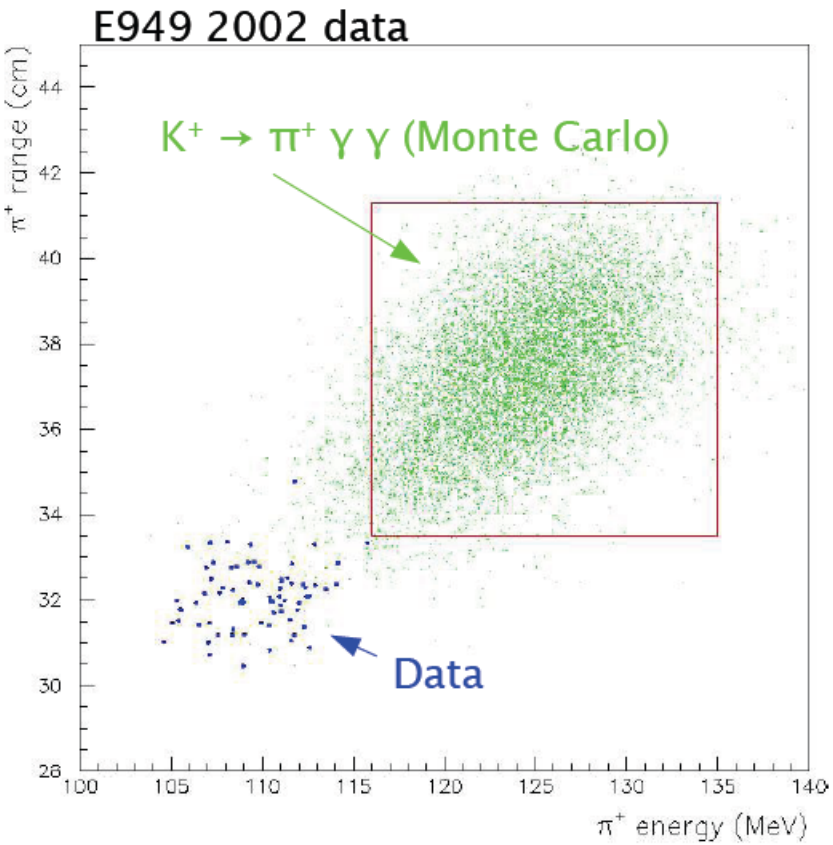


Backgrounds	Number of Events
Kπ2	0.017 ± 0.006
Overlapping Photon	0.065 ± 0.065
Muon	0.090 ± 0.020
K decay in flight	0.025 ± 0.014
Two Beam	<0.006 (90%CL)
Total	0.197 ± 0.070

	including unitarity corrections $\hat{\epsilon} = 1.8$	without the corrections $\hat{\epsilon} = 1.6$
Total acceptance ($P_{\pi+} > 213$ MeV/c)	$(2.99 \pm 0.07) \times 10^{-4}$	$(1.10 \pm 0.04) \times 10^{-4}$
N_K	1.19×10^{12}	
K^+ stopping efficiency ($K_{\pi 2}$ decays in the trigger)	0.754 ± 0.024	
Single Event Sensitivity	$(3.72 \pm 0.14) \times 10^{-9}$	$(10.1 \pm 0.5) \times 10^{-9}$
predicted branching ratio ($P_{\pi+} > 213$ MeV/c)	6.10×10^{-9}	0.49×10^{-9}
expectation	1.6 events	0.05 events

$K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\gamma$ results





Blind analyses. No events seen in signal boxes

$Br(K^+ \to \pi^+\gamma\gamma) < 8.3 \times 10^{-9}$ (90%CL)

$p(\pi) > 213$ MeV/c

Assuming spectrum from ChPT with unitarity corrections (c = 1.8)

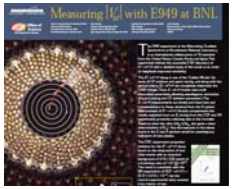
Factor of 8 sensitivity improvement over E787; but, cannot confirm or rule of unitarity corrections. With a full 60 week run we would have been x10 more sensitive.

Same data set is used to search for $K^+ \to \pi^+\gamma$ which *only* violates angular momentum conservation and gauge invariance

$Br(K^+ \to \pi^+\gamma) < 2.3 \times 10^{-9}$ (90%CL)

Factor of 160 improvement over E787

$\pi^0 \to \nu\ \bar{\nu}$



- Forbidden by angular momentum conservation if W's and neutrinos are purely left handed. Can proceed if neutrinos have mass.

  $Br(\pi^0 \to \nu\ \bar{\nu}) < 1.1 \times 10^{-9}$ for $m(\nu_\tau)<18.2$ MeV/c^2

- Best previous limit comes from E787

  $Br(\pi^0 \to \nu\ \bar{\nu}) < 8.3 \times 10^{-7}$ (90%CL)

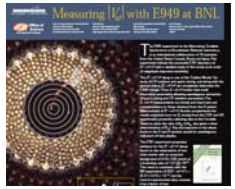
- Method:

  Copious supply of clean π^0 from $K^+ \to \pi^+\pi^0$ tagged by monochromatic π^+.

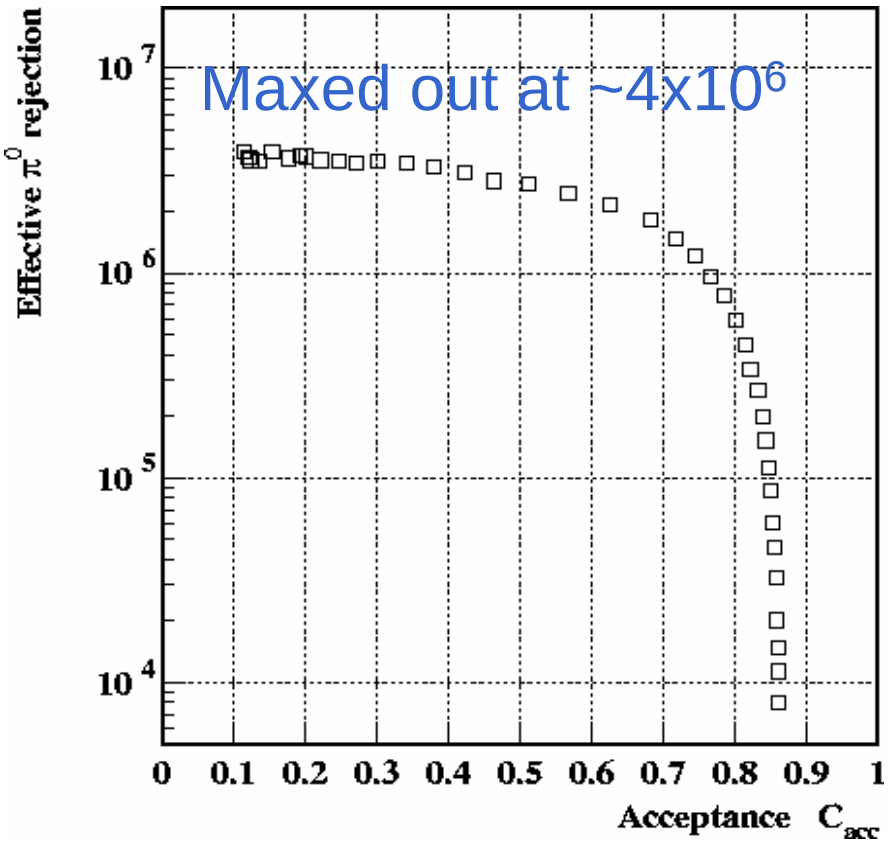
  Look for $K\pi 2$ events with no activity other than K^+ and π^+.

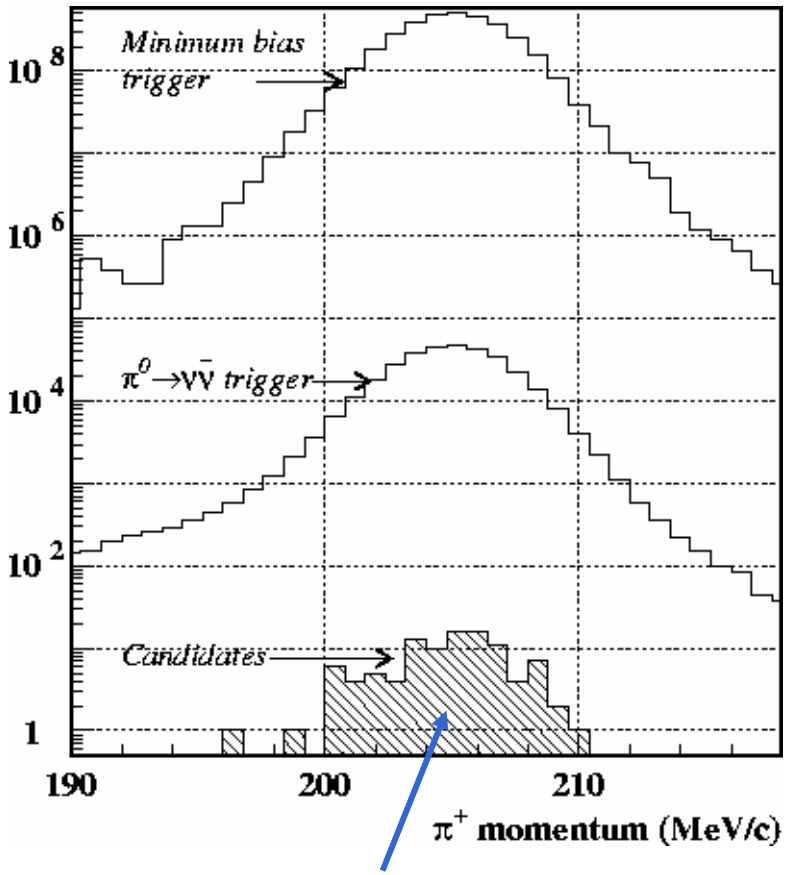
  Trigger sample is same as $K^+ \to \pi^+ \nu\ \bar{\nu}$. Select $K\pi 2$ events; apply tightest photon veto.

  Tune photon veto on 1/3 of data, use other 2/3 for search.



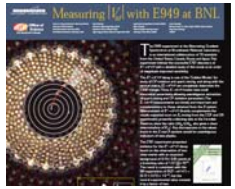
$\pi^0 \to \nu\ \bar{\nu}$ π^0 Rejection





99 events survive all cuts

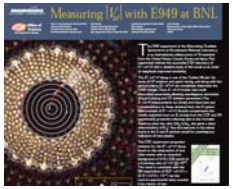
$\pi^0 \to \nu\ \bar{\nu}$ Results



- 99 events remain after all photon veto cuts
- We presume these to be $\pi^0 \to \gamma\gamma$ with undetected photons
  - The e949 photon veto inefficiency in not known and probably not knowable at this level.
  - A background subtraction is not a reasonable option.
- The corresponding branching ratio upper limit is:

  $Br(\pi^0 \to \nu\ \bar{\nu}) < 2.7 \times 10^{-7}$ (90%CL)

  Factor of 3 improvement beyond E787



Conclusions

- Present E949 results

  $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.5\ ^{+1.3}_{-0.9}) \times 10^{-10}$ [3 events, E787(2) + E949(1)]

  $Br(K^+ \rightarrow \pi^+ \gamma\gamma) < 8.3 \times 10^{-9}$ (90%CL) $p(\pi) > 213$ MeV/c

  $Br(K^+ \rightarrow \pi^+ \gamma) < 2.3 \times 10^{-9}$ (90%CL)

  $Br(\pi^0 \rightarrow \nu \bar{\nu}) < 2.7 \times 10^{-7}$ (90%CL)

- Expected new E949 Results

  $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ from region below Kp2 peak

- Further Progress in ultra-rare Kaon decays

  Not in the US, P326(Cern), Jparc(Japan)

References

$K^+ \rightarrow \pi^+ \gamma\gamma$, $K^+ \rightarrow \pi^+ \gamma$

T. Yoshioka, Univ. of Tokyo thesis, KEK K-decay Report 2005-2, Hep-ex/0505069, Phys.Lett.B 623 (2005) 192-199

$\pi^0 \rightarrow \nu \bar{\nu}$

K.Mizouchi, Kyoto Uinv. Thesis (in preparation), hep-ex/0506028, submitted to Phys.Rev.D. Rapid Communications